

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 074-0188	
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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 1995		3. REPORT TYPE AND DATES COVERED Technical Paper 1995
4. TITLE AND SUBTITLE Technical Status of the Dish/Stirling Joint Venture Program			5. FUNDING NUMBERS DOE Contract DE-AC04-94-AL85000	
6. AUTHOR(S) J.R. Bean, R.B. Diver				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Cummins Power Generation, Inc. P.O. Box 3005, MC 60125 Columbus, IN 47202			8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) SERDP 901 North Stuart St. Suite 303 Arlington, VA 22203			10. SPONSORING / MONITORING AGENCY REPORT NUMBER N/A	
11. SUPPLEMENTARY NOTES Technical paper, Issue No. 95-202, 1995. This work was supported in part by Dept. of Energy under Contract No. DE-AC04-94-AL85000. The United States Government has a royalty-free license throughout the world in all copyrightable material contained herein. All other rights are reserved by the copyright owner.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release: distribution is unlimited			12b. DISTRIBUTION CODE A	
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14. SUBJECT TERMS SERDP, CPG, DOE, clean technology, solar energy, free-piston engine			15. NUMBER OF PAGES 8	
			16. PRICE CODE N/A	
17. SECURITY CLASSIFICATION OF REPORT unclass	18. SECURITY CLASSIFICATION OF THIS PAGE unclass	19. SECURITY CLASSIFICATION OF ABSTRACT unclass		20. LIMITATION OF ABSTRACT UL

19980806 047

TECHNICAL STATUS OF THE DISH/STIRLING JOINT VENTURE PROGRAM

John R. Bean
Cummins Power Generation, Inc.
P.O. Box 3005, MC 60125
Columbus, Indiana 47202
(812) 377-3543 / (812) 377-4453 fax

Richard B. Diver
Sandia National Laboratories
P.O. Box 5800, MS 0703
Albuquerque, New Mexico 87185
(505) 844-0195 / (505) 844-7786 fax

ABSTRACT

Initiated in 1991; the Dish/Stirling Joint Venture Program (DSJVP) is a 5-year, \$17.2 million joint venture which is funded by Cummins Power Generation, Inc. (CPG) of Columbus, Indiana and the United States Department of Energy's (DOE) Solar Thermal and Biomass Power Division. Sandia National Laboratories administers and provides technical management for this contract on the DOE's behalf. In January, 1995; CPG advanced to Phase 3 of this three-phase contract. The objective of the DSJVP is to develop and commercialize a 7-kW_e Dish/Stirling System for remote power markets by 1997.

In this paper, the technical status of the major subsystems which comprise the CPG 7-kW_e Dish/Stirling System is presented. These subsystems include the solar concentrator, heat pipe receiver, engine/alternator, power conditioning, and automatic controls.

INTRODUCTION

Initiated in 1991; the Dish/Stirling Joint Venture Program (DSJVP) is a 5-year, \$17.2 million joint venture which is funded by Cummins Power Generation, Inc. (CPG) of Columbus, Indiana and the United States Department of Energy's (DOE) Solar Thermal and Biomass Power Division (Bean and Diver, 1992). Sandia National Laboratories administers and provides technical management for this contract on the DOE's behalf. In January, 1995; CPG advanced to Phase 3 of this three-phase contract. The objective of the DSJVP is to develop and commercialize a 7-kW_e Dish/Stirling System for remote power markets by 1997. To support this objective, CPG has structured the DSJVP's development effort to be consistent with Cummins Engine Company guidelines for *New Product Planning, Development, and Introduction*.

Cummins is the leading worldwide designer and manufacturer of fuel-efficient diesel engines ranging from 76 to 2,000 horsepower. These engines power a wide variety of equipment in Cummins' key markets: heavy-duty truck, midrange truck, power generation, bus and light commercial vehicles, industrial products, marine, and government. In 1994, Cummins' sales exceeded \$4.7 billion. CPG is a wholly-owned subsidiary of Cummins.

In the mid-1980's, Cummins identified Dish/Stirling as a viable, *clean* technology for both remote and utility power generation markets. Since then, Cummins has invested heavily in the development of Dish/Stirling Technology. Besides the DSJVP, CPG is also participating in the Utility Scale Joint Venture Program (USJVP); a 5-year, \$32 million joint venture which is also funded by CPG and the DOE's Solar Thermal and Biomass Power Division. As with the DSJVP, Sandia administers and provides technical management for this contract on the DOE's behalf. The objective of the USJVP is to develop and commercialize a 25-kW_e Dish/Stirling System for utility power markets by 1999. Having commenced in 1994, the USJVP is currently in Phase 1 of a three-phase contract.

Specifications for the CPG 7-kW_e Dish/Stirling System are provided in Table 1. The system consists of the following six major subsystems: concentrator, heat pipe receiver, free-piston Stirling engine with linear alternator, power conditioning, automatic controls, and cooling system (Bean and Diver, 1993). In normal operation, the concentrator tracks the sun in two axes and focuses sunlight through the aperture onto the heat pipe receiver. The heat pipe receiver serves as a thermal buffer to the Stirling engine's heater head by providing an isothermal temperature distribution through condensation of the sodium on the heater head tubes. The free-piston Stirling engine converts the thermal energy into mechanical energy, and the linear

Power Delivered:	7 kW _e (net) at 950 W/m ² 240 Volts nominal 60 Hertz nominal Single phase
System Durability:	
Completion of DSJVP	2,000 hours
Commercial Product	40,000 hours
System Reliability:	
Completion of DSJVP	200 hours MTBF
Commercial Product	4,000 hours
Potential Applications:	Remote village electrification Remote water pumping Utility grid-tie
Special Features:	Automatic start-up/operation Hybrid option

Table 1 - CPG 7-kW_e Dish/Stirling System Specifications

alternator converts the mechanical energy into single-phase electrical power. Power conditioning hardware regulates and conditions this power such that it will be suitable for practical use. Waste heat from the Stirling engine is transferred to the atmosphere by the cooling system. Automatic control of the overall Dish/Stirling System is provided by the integrated control system (ICS).

The following sections describe the technical status of the major subsystems and related components.

CONCENTRATOR

The CPG-460 solar concentrator technology is a modification of the LaJet Energy Company LEC-460 design. A photograph of a CPG-460 concentrator operating at the California State Polytechnic University (Cal-Poly) test site is shown in Figure 1. The principal features of the CPG-460 concentrator are a geodesic, space-frame, mirror-support structure; a diurnal (polar axis) drive, pivoted near the center of gravity of the tracking structure; and stretched-membrane, silvered, polymer-film mirror facets. The concentrator consists of 24 stretched-membrane mirror facets, each 1.524 meters (60 inches) in diameter. Each facet consists of an edge-supported, silvered, 3M ECP-305+ acrylic film laminated to polyethylene terephthalate (PET) film on the front surface and an aluminized PET film on the rear surface. Focus of the mirrors is maintained by a small vacuum in the cavity between the two films. The correct mirror curvature is provided by a tube mounted to the rear membrane that modulates flow by closing against the front membrane. Emergency defocus of the system is accomplished by venting the mirror cavity to atmosphere.

During Phase 2 of the DSJVP, the mirror facet reflective material was changed from aluminum to silver (3M ECP-305+). The change was implemented primarily to improve mirror reflectivity. With aluminized mirrors, the reflectivity of a new mirror and a washed, used mirror was 86% and 78%, respectively. With silvered mirrors, the reflectivity of a new mirror and a washed, used mirror is 93% and 87%, respectively.

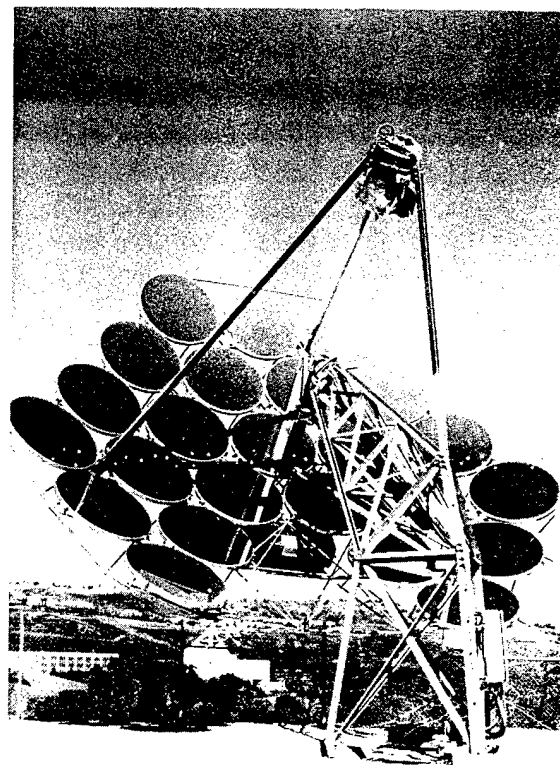


Figure 1 - CPG-460 at Cal-Poly (Pomona, CA)

At present, ten CPG-460 solar concentrators are employed in the field: four at the CPG-South Solar Test Facility (Abilene, Texas), one at the Thermacore test site (Lancaster, Pennsylvania), one at the Cal-Poly test site (Pomona, California), one at the Texas Utilities Energy Park (Dallas, Texas), and three at Aisin-Seiki test facilities (Nice, France and Miyako Jima, Japan). Combined, these units have accumulated over 20,000 tracking hours. Two units installed at the CPG-South Solar Test Facility have each tracked the sun for over 5,000 hours. Most of the failure incidents encountered throughout the testing of these ten units have been corrosion-related. Mirror *tunneling* of the 3M ECP-305+ silver film and fluctuating optical characteristics as a function of weather conditions have been persistent issues. With the exception of some initial oil leakage issues, the mechanical actuator assembly has performed consistently well.

The optical accuracy of the CPG-460 concentrator has continued to improve. The peak flux intensity of the CPG-460 was measured with Sandia's Beam Characterization System (BCS) at approximately 700 W/cm² (normalized to 1,000 W/m² direct normal insolation) in August, 1994. This compares with a peak flux intensity of approximately 550 W/cm² measured in March, 1993. This equates to a 27% improvement in the peak flux intensity. Alignment and focus of the 24 mirror facets with a *near light source* alignment technique has continued to be refined, with support from Sandia (Diver, 1995). A photograph

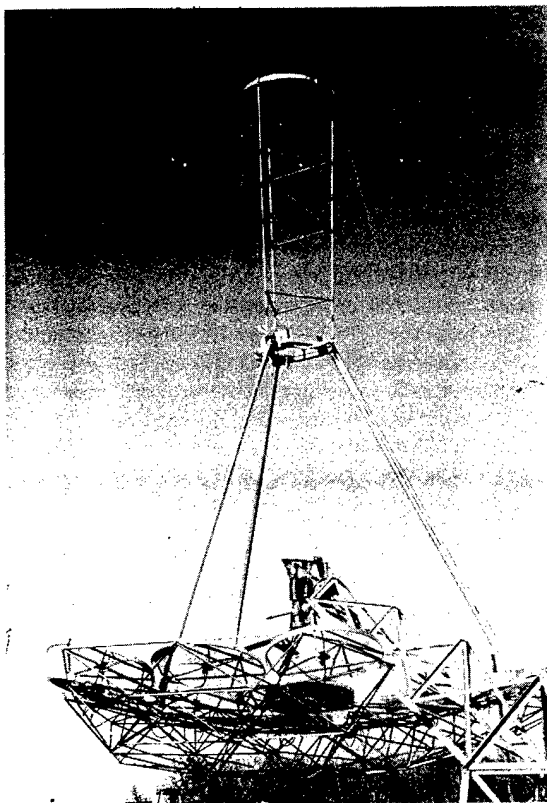


Figure 2 - Alignment Fixture Mounted to CPG-460

of the *near light source* alignment fixture is shown in Figure 2. The technique uses an artificial light source and target located on a special fixture at one focal length behind the concentrator's focal point. The technique is being developed for use at remote sites.

A surface-reactive foundation design was developed as an alternative to the conventional deep-drilled pier design. This first surface-reactive foundation design was specifically for expansive soils (clay) such as the soil at the CPG-South Solar Test Facility. A prototype surface-reactive foundation has been installed at this test facility. Three additional designs for sand, rock, and soils with deep frost lines will be generated during Phase 3 of the DSJVP. The surface-reactive design option is intended to be suitable for remote Dish/Stirling installations. In general, the surface-reactive foundation uses less concrete, can be dug with a backhoe or shovels, and does not require the soil analysis needed to confirm the acceptability of a deep-drilled pier foundation.

During Phase 3 of the DSJVP, CPG will explore the feasibility of glass mirror panels for the CPG-460 concentrator. Since glass mirror panels are the prime path for the 100 kW_t concentrator for the USJVP, the DSJVP will allow the USJVP to take the lead in validating the manufacturing processes and optical quality. If the decision is made to pursue glass panels for the DSJVP, a space frame redesign will be necessitated. Also, a

redesign of the declination drive assembly is planned in order to simplify assembly and improve durability/reliability. Finally, an aggressive corrosion control program will be defined and implemented.

HEAT PIPE RECEIVER

To provide thermal energy to the heater head tubes of the Stirling engine in a uniform, efficient manner, a heat pipe receiver serves as a buffer between the solar concentrator and the Stirling engine. With a heat pipe receiver, the non-uniform fluxes generated by the solar concentrator are directed onto the heat pipe receiver's solar absorber instead of onto the relatively fragile heater head tubes. This eliminates a major durability concern associated with directly-illuminated heater heads. In addition, heat pipe receivers enable the heater head tubes to remain isothermal during engine operation, resulting in higher average heater head tube temperatures and correspondingly higher engine/alternator efficiencies. The Thermacore (Lancaster, Pennsylvania) heat pipe receiver transfers heat by evaporating sodium from the backside of a 0.416 meter (16.3 inch) diameter hemispherical solar absorber and condensing it on the heater head tubes of the Stirling engine. The liquid sodium is returned to the absorber by both gravity (refluxing) and preferentially-located liquid return ducts and is distributed over the absorber by capillary forces in the sintered nickel powder wick.

In a parallel effort, Sandia and Porous Metal Products, Inc. have developed an alternative sintered felt-wick design (Andraka et al., 1995). The felt-wick heat pipe receiver design appears to have performance, cost, and manufacturability advantages over the nickel-powder-wick design. However, both the nickel-powder-wick and the felt-wick technologies have the potential to meet CPG's durability/reliability, performance, and cost targets.

At this time, durability/reliability is the primary issue for both the nickel-powder-wick and felt-wick designs. In conjunction with the DSJVP, the National Renewable Energy Laboratory (NREL) has sponsored Durability Heat Pipe Receiver Projects, aimed at understanding long-term durability issues associated with heat pipe receivers. These heat pipe receivers have been tested on-sun with a gas-gap calorimeter (to simulate a Stirling engine) to accurately measure receiver performance and to accumulate operating hours. Three heat pipe receivers, each with Thermacore sintered nickel-powder-wick designs, have been built and tested in conjunction with NREL. As a result of ongoing wick improvements, each durability heat pipe receiver has performed significantly better than its predecessor. During 1991, durability heat pipe receiver #1 accumulated 367 hours prior to a wick-related failure. During 1992, durability heat pipe receiver #2 accumulated 600 hours prior to another wick-related failure. Durability heat pipe receiver #3, which incorporated liquid return ducts but no circumferential arteries, accumulated 2,074 hours of on-sun operation from April, 1993 through November, 1994. Nominal heat throughput at 950 W/m² insolation was 22 to 24 kW_t. This unit was voluntarily

taken out of service to make the concentrator available for on-sun testing of a felt-wick heat pipe receiver. This decision has provided a unique opportunity to dissect and evaluate a heat pipe receiver that has been tested extensively in the field but has not yet failed. A detailed evaluation of the wick is being performed by Sandia.

To assess the low cycle fatigue issue caused by daily heat up and cool down (i.e., ambient temperature to 675°C to ambient temperature), a Thermacore test cell has been dedicated to around-the-clock heat pipe receiver cycle testing. A quartz lamp array simulates the solar heat input. The test plan calls for an aggressive, 10-minute warm-up; a one-hour heat soak at 675°C; and an accelerated, two-hour cool down. Consequently, each cycle requires approximately three hours. During steady-state operation at 675°C, approximately 26 kW_t of heat throughput is delivered to the gas-gap calorimeter. Durability heat pipe receiver #4, which incorporated both liquid return ducts and two redundant circumferential arteries, endured 2,794 hours and 1,160 thermal cycles prior to a weld failure.

Thermacore and Sandia have collaborated on an effort to develop and refine heat pipe receiver performance prediction capabilities. The resulting simulation code has been verified, to a large extent, through hardware testing of three different heat pipe receiver designs. Both the sintered nickel-powder-wick and the sintered felt-wick designs have exceeded CPG's 36 kW_t heat throughput specification during limited testing on Sandia's Test Bed Concentrator. In fact, the sintered nickel-powder-wick design demonstrated 116 kW_t heat throughput capability when tested at Sandia using a field of heliostats as the heat input source.

Through another NREL program, Thermacore has designed, built, and tested a prototype hybrid heat pipe receiver (Hartenstine and Dussinger, 1994). Hybridization enables the available solar resource to be augmented with the heat generated from natural gas burners to provide a nearly constant thermal power to a free-piston Stirling engine. This enables the Dish/Stirling System to operate at full power and peak efficiency at any time, 24-hours-per-day. Hybridization is particularly attractive to many utilities because it allows Dish/Stirling Systems to operate at full output power during a utility's high-demand periods, regardless of the available insolation. For example, in the summer months, these high-demand periods are typically in the late afternoon or early evening when air conditioning is required. In the winter months, the high-demand periods are at night for residential and commercial heating.

During the first quarter of 1995, Thermacore tested the prototype hybrid heat pipe receiver using natural gas burners, quartz lamps, or combinations of both natural gas burners and quartz lamps as the heat input source(s). The quartz lamps are used to evaluate the performance of the hybrid receiver during simulated solar-only and simulated dual-mode (i.e., solar plus natural gas) operation. The prototype hybrid receiver includes a condenser and gas-gap calorimeter to simulate the heater head tubes of a Stirling engine.

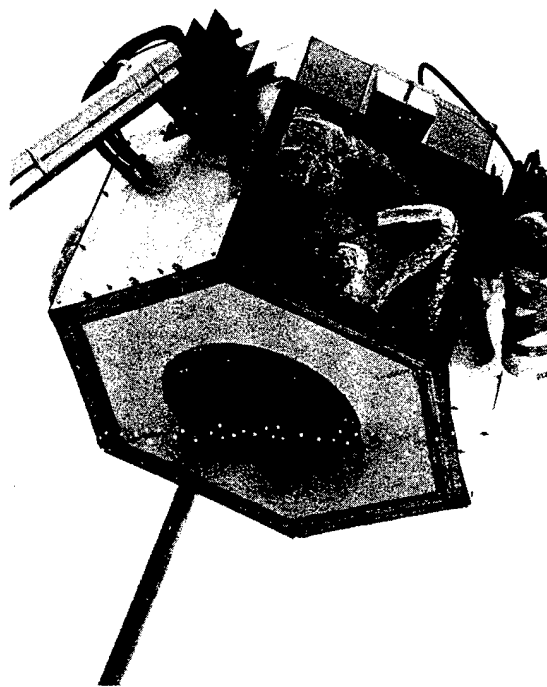


Figure 3 - On-Sun Testing of Hybrid Receiver

Over the course of this testing, the prototype hybrid receiver successfully operated for 65 hours: 47 hours in the natural gas-only operating mode and 18 hours in the natural gas-plus-quartz lamp operating mode. The hybrid receiver was tested in the stow position and at angles of 30°, 60°, and 75° from the stow position. In the natural gas-only mode, a maximum of 20 kW_t was delivered to the gas-gap calorimeter during full-power thermal input from the gas burners of 44 kW_t. The resulting thermal efficiency, 45 to 50%, is considerably lower than the 80% design target. This is because Thermacore's current configuration does not incorporate an air preheater. In the natural gas-plus-quartz lamp operating mode, a maximum of 33 kW_t was delivered to the gas-gap calorimeter: 20 kW_t from natural gas and 13 kW_t from quartz lamps. These maximum powers were achieved at each of the orientations noted above.

CPG and Thermacore have installed and initiated testing of the prototype hybrid heat pipe receiver on a CPG-460 solar concentrator at the CPG-South Solar Test Facility in Abilene, Texas. A photograph of this installation is shown in Figure 3. To date, the hybrid receiver has successfully operated on-sun for over 50 hours. During this initial on-sun testing, the natural gas and air flow conditions are being controlled manually. Later, these control features will be automated.

As Phase 3 of the DSJVP has begun, Thermacore has initiated the development of a second-generation hybrid heat pipe receiver. This redesign will respond to several shortfalls associated with the prototype design which include low thermal efficiency and excessive cost, weight, and physical size. CPG

and Thermacore expect to conduct on-sun testing of second-generation hardware by the end of 1995. Besides hybridization, Thermacore's primary Phase 3 tasks include durability/reliability testing of both the nickel-powder-wick and felt-wick technologies and cost reduction of the overall heat pipe receiver.

ENGINE/ALTERNATOR

The CPG 7-kW_e Dish/Stirling System employs a free-piston Stirling engine with linear alternator. The free-piston Stirling engine converts thermal energy into mechanical energy and the linear alternator converts this mechanical energy into single-phase AC electrical power. The engine/alternator can be hermetically sealed and has only four moving parts (in the opposed-twin configuration), making it a potentially long-lived and reliable power generator.

During Phase 2 of the DSJVP, CPG encountered major development problems with the engine/alternator technology. In January, 1994, Clever Fellows Innovation Consortium, Inc. (CFIC) (Troy, New York) was elevated to the position of prime-path engine/alternator developer for the DSJVP. CFIC had spent the past two years developing an engine/alternator design which had several attractive commercialization features.

Prior to that, Sunpower, Inc. (Athens, Ohio) had been CPG's prime-path engine/alternator developer. Given Sunpower's three-year head start, CPG had anticipated that Sunpower would remain the prime-path engine/alternator developer, at least through the completion of the DSJVP. Since 1988, CPG had supported Sunpower in the development of an engine/alternator which would be compatible with CPG's solar concentrator technology. An early Sunpower prototype engine/alternator was installed and operated on a CPG concentrator in 1989. In 1992 (Phase 1 of the DSJVP), a second-generation Sunpower engine/alternator demonstrated 7-kW_e output power and 28% engine/alternator efficiency. CPG and Sunpower jointly manufactured three additional copies of this design. Later in 1992, CPG authorized Sunpower to develop a third-generation engine/alternator with the following performance goals: 9-kW_e output power and 30% engine/alternator efficiency (Bean and Diver, 1993).

By the end of 1993, Sunpower's third-generation engine/alternator design had experienced several major setbacks. The most critical of these setbacks was a design oversight related to the flow distribution of the working gas (helium) within Sunpower's novel heater head design which rendered the design, and a considerable amount of hardware, useless. CPG projected that Sunpower would require at least six months to recover from this mistake. At the same time, CFIC's prototype 6 kW_e engine/alternator (first-generation design) began operating with considerable success in the CFIC test cell. Based on this turn of events, CPG and Sandia jointly agreed that the CFIC technology should be elevated to prime-path status.

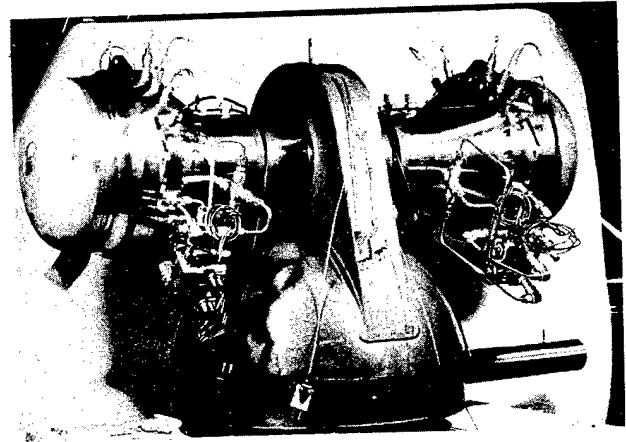


Figure 4 - CFIC Twin-Opposed Free-Piston Stirling Engine

The CFIC technology, with its flexure-supported STARTM alternators, is considered to be more attractive for commercialization because of its superior manufacturability (Corey and Yarr, 1992). Also, with its opposed-twin configuration, the CFIC technology eliminates major vibration-related problems experienced with the Sunpower single-cylinder design during Phase 1. A photograph of the CFIC engine/alternator on a test cell heat pipe is shown in Figure 4.

Unfortunately, continued development of the CFIC technology and transfer of CFIC's technology to CPG over the past 15 months has progressed much more slowly than expected. To date, CFIC has demonstrated a maximum output power of 5.2 kW_e and a maximum engine/alternator efficiency of 22% with interim regenerators. CPG and CFIC have jointly manufactured three additional copies of this design. After nine months of testing at CPG-South, these additional copies are finally approaching the performance of CFIC's initial prototype engine/alternator. As a result of these delays associated with the engine/alternator development, previously with the Sunpower technology and now with the CFIC technology, Phase 2 of the DSJVP required 24 months to complete instead of the originally planned 12 months. Correspondingly, several field test system installations have had to be postponed due to the unavailability of reliable engine/alternators.

Despite these major development problems, CPG remains optimistic about the potential of the CFIC engine/alternator technology. CPG and CFIC engineers and technicians are working together to meet the near-term hurdles: achieving a reliable engine/alternator, resuming on-sun system integration testing at the CPG-South Solar Test Facility, and manufacturing two additional copies to meet immediate field test system commitments. For Phase 3 of the DSJVP, several potential design improvements are in various stages of implementation. Alternative materials for displacer seals, piston seals, and displacer bearings are being evaluated. With analytical support from Sandia, CFIC is incorporating several heat exchanger flow distribution improvements, including a revised regenerator assembly which eliminates bypass leakage. To achieve 9-kW_e,

output power, the alternator assembly is being upscaled. Also, the material selection for the hot-end components is changing from 347 Stainless Steel to Inconel 625, which has been shown analytically to improve performance without a manufacturing cost penalty.

CPG is in the process of staffing its own Stirling Engine Development and Manufacturing Groups. By the end of 1995, these two groups will consist of approximately ten people. Over the past nine months, CPG has assumed responsibility for purchasing of parts, inspection, assembly, and testing of CFIC's first-generation design. Over the next few months, CPG will take the lead on drawing maintenance and reliability testing of several key components including flexure straps, alternator coils, and complete alternator assemblies. Besides continuing to support the technology transfer from CFIC to CPG, CFIC's principal role for the foreseeable future is to focus its efforts on performance development.

To support the DSJVP and USJVP efforts, CPG's headcount will nearly double during 1995. Nearly half of these new employees will support the engine/alternator development. Later this summer, CPG's research and development personnel in Abilene, Texas (CPG-South) will move from their current 8,250 square-foot facility to a refurbished, 50,000 square-foot facility. Recognizing the criticality of the engine/alternator development, this facility will include eight engine test cells.

POWER CONDITIONING

The power conditioning hardware regulates and conditions the electrical energy generated by the free-piston Stirling engine's permanent-magnet linear alternator so that this electrical energy is suitable for practical use. Since most of the field test hosts for Phase 3 of the DSJVP are domestic utilities, the utility grid-tie application (UGA) was chosen as the baseline design. The water pumping application (WPA) and the remote village electrification application (RVE) will be developed during Phase 3.

During Phase 2, CPG and CFIC made a fundamental change in the power conditioning approach for the 7-kW_e Dish/Stirling System. The current approach utilizes solid state power conditioning electronics to rectify the AC power from the linear alternators into DC power and invert this power into 60 Hz, 240 VAC power. This approach was determined to be more cost effective than direct coupling of the linear alternator to the load because: (1) it results in higher engine/alternator efficiencies at part load (versus displacer damping); (2) it allows engine operation at higher frequencies and, therefore, higher output power; and (3) it permits the alternator to operate in a saturated condition, therefore achieving higher output power for a given alternator design. Solid state power conditioning is adaptable to the various applications of the 7-kW_e Dish/Stirling System and permits the production of three-phase power. The solid state power conditioning hardware is approximately 92% efficient and includes voltage, current, and frequency protection for the utility grid.

To assess the durability of the power conditioning hardware, a test has been devised in which grid power from two legs of a three-phase electrical service is input to the power conditioning hardware and the output is supplied to a separate 240 VAC single-phase service. The purpose of this test set-up has been to enable durability testing of power conditioning hardware to proceed in the absence of a reliable engine/alternator. To date, one unit has operated for over 2,000 hours; a second unit has operated for over 1,000 hours.

During Phase 3, development efforts will focus on improving the UGA power conditioning hardware's efficiency, preparing for larger-scale manufacturing, and reducing the unit cost. In addition, WPA power conditioning hardware and RVE power conditioning hardware will be developed.

The WPA power conditioning hardware will consist of a three-phase variable voltage and frequency motor controller to power a submersible water pump. Voltage and frequency will vary to match the available solar energy. To keep unit cost as low as possible, an off-the-shelf pump will be identified. To support WPA testing, a well will be drilled at the CPG-South Solar Test Facility.

The RVE application development will require the design of a power management system that will utilize available alternator power to supply power to a small, independent power network for use in a remote area. The alternator power will have the capability to be augmented by batteries during periods of low insolation. To support RVE testing, a portable building will be situated at the CPG-South Solar Test Facility to simulate a remote, independent-user environment. Typical user loads such as incandescent lighting, a television, and a refrigerator will be housed in this portable building.

AUTOMATIC CONTROLS

The integrated control system (ICS) controls the overall CPG Dish/Stirling System. By monitoring vital system functions, the ICS checks for out-of-tolerance conditions, makes system adjustments when necessary, notifies the human operator of problems requiring his attention, logs any faults that are detected, and takes action to protect the system when a failure occurs. In the event of a failure which requires engine/alternator operation to be terminated quickly, the overstroke/kill module provides electrical damping by placing a low-impedance load across the alternator.

At the beginning of Phase 2 of the DSJVP in January, 1993, CPG assumed responsibility for the controls development and manufacturing. Upon assuming controls responsibility, CPG identified two primary objectives. First, it was determined that an embedded control system for design qualification testing and evaluation which is representative of today's commercially-available production systems should be aggressively pursued. Second, integrating data acquisition for field test units into the control system to allow for more complete data collection of actual controls operating parameters, reduce field wiring

requirements, and enhance and streamline the data reduction process was established as a top priority. Several industry observations factored into the definition of CPG's development path: (1) embedded PC's for machine control have become a significant trend (many systems are available for many applications); (2) the INTEL 386ex promises to set a new cost/performance benchmark; and (3) the "C" and "C++" computer languages are clearly the leaders in embedded systems software.

Based on these primary objectives and industry observations, CPG defined its controls development architecture. CPG selected an embedded PC which plugs into a card cage mounted in a NEMA 4 enclosure box at the base of the solar concentrator. Controls hardware includes an off-the-shelf 386sx CPU with ISA bus and passive backplane which utilizes the OCTAGON Micro PC form factor, a custom digital I/O interface board, a custom analog input interface board, a custom thermocouple input interface, and custom power supplies and AC solid-state relay circuits.

The controls software operating environment consists of the "C++" language, TICS Real Time Kernel, and ROM-DOS. Sun position algorithms developed by NREL have been converted from the FORTRAN code to "C++" (NREL, 1992). The Sandia-developed *SOLARTRAK* structural misalignment algorithms have been implemented and adapted for use with CPG's polar-axis tracking system (Maish, 1991). The engine/alternator and cooling system control software has been converted to "C++". Portions of CPG's former concentrator control and handheld interface software has been converted to "C++". Numerous new control, data acquisition, and user interface functions have been developed and implemented.

Solar concentrator tracking software incorporating the NREL sun position formulas, the Sandia structural misalignment code, and CPG's closed-loop tracking procedures has proven to be very effective. Misalignment of the solar concentrator of up to $\pm 2.5^\circ$ in either the declination or polar axis can be tolerated without negatively impacting the performance of the system. This inherent adaptability of the controls software simplifies the installation of the solar concentrator. In the past, the north/south alignment of the concentrator and the concentrator's latitude interface had to be very precise in order for the concentrator to track properly. Also, if the system was not tracked for several days, the concentrator would have to be targeted manually once on-sun operation resumed. With the current system, tracking data from the past several operating days is used to predict appropriate open-loop tracking corrections for the upcoming operating day. Currently, five CPG concentrators employ the new controls software. Each of these systems, even after several days of inactivity, are able to *wake up* and automatically find the sun position well within the closed-loop capture range. This represents a major milestone in CPG's ongoing efforts to achieve a fully *stand-alone* system.

In order for the CPG Dish/Stirling System to be truly *stand-alone*, the ICS must sense solar and wind conditions to

determine if system operation is warranted and safe. The ICS utilizes a pyranometer to assess whether or not sufficient solar energy is available to warrant the parasitic power loss associated with system initialization and start-up. To protect the system, an anemometer detects when the wind speed exceeds a pre-defined fault threshold. When this out-of-tolerance condition occurs, the solar concentrator is returned to the stow position, the orientation which minimizes wind loading on the concentrator's structure.

CPG's integrated control system provides three user interfaces. For normal, everyday use; panel-mounted buttons and switches at the base of the solar concentrator allow a system operator to impart basic system commands. For servicing, a hand-held data terminal enables a technician to review fault data, change operating parameters, and manually operate the system. For remote accessibility, a modem interconnect allows off-site personnel to monitor system operation for diagnostic purposes, download performance and fault data to facilitate further engineering development, and install software upgrades as they become available.

SUMMARY

Initiated in 1991; the Dish/Stirling Joint Venture Program (DSJVP) is a 5-year, \$17.2 million joint venture which is funded by Cummins Power Generation, Inc. (CPG) and the United States Department of Energy's (DOE) Solar Thermal and Biomass Power Division. In January, 1995; CPG advanced to Phase 3 of this three-phase contract. The objective of the DSJVP is to develop and commercialize a 7-kW_e Dish/Stirling System for remote power markets by 1997.

The DSJVP has continued to make major progress. During Phase 2 of the DSJVP (January, 1993 through December, 1994); the concentrator, heat pipe receiver, power conditioning, and automatic controls development exceeded expectations in terms of both performance and durability/reliability. Each of these subsystems has demonstrated thousands of hours of successful operation.

Engine/alternator development continues to constitute the critical path. A major program deviation occurred in January, 1994 when Clever Fellows Innovation Consortium, Inc. (CFIC) was elevated to the position of prime-path engine/alternator developer for the DSJVP. The CFIC technology is considered to be more attractive for commercialization because of its superior manufacturability. These same design advantages have made prototype development more complicated. Despite the numerous technical challenges being encountered in the development of the CFIC technology, CPG remains confident that the CFIC technology will ultimately result in a commercial product.

During Phase 3 of the DSJVP; durability/reliability testing and cost reduction for individual subsystems, as well as the complete Dish/Stirling System, will be major points of emphasis. Twelve field test systems will be manufactured, installed, and field tested. Likely field test hosts include Texas

Utilities (Dallas, Texas); California State Polytechnic University (Pomona, California); Central and South West Services (Fort Davis, Texas); Nevada Power Company (Las Vegas, Nevada); Georgia Tech University (Atlanta, Georgia); AT&T (Phoenix, Arizona); and Sandia National Laboratories (Albuquerque, New Mexico).

ACKNOWLEDGEMENTS

This work is supported by Cummins Power Generation, Inc. and the United States Department of Energy under contract DE-AC04-94-AL85000. The authors would like to once again acknowledge the technical contributions and dedication of all Dish/Stirling Joint Venture Program participants at CPG, CPG-South, Thermacore, and CFIC. Invaluable technical contributions by engineers and scientists at Sandia and NREL continue to make this a true *joint venture* and are very much appreciated.

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